ENGINE STRUCTURES COMPUTATIONAL SIMULATION METHODS

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Abstract

Select computer codes developed over the years to simulate specific aspects of engine structures are described with typical results to illustrate their capability. These codes include blade impact integrated multidisciplinary analysis and optimization, progressive structural fracture, quantification of uncertainties for structural reliability and risk, benefits estimation of new technology insertion and hierarchical simulation of engine structures made from metal matrix and ceramic matrix composites. Collectively these codes constitute a unique infrastructure readiness to credibly evaluate new and future engine structural concepts throughout the development cycle from initial concept, to design and fabrication, to service performance and maintenance and repairs, and to retirement for cause and even to possible recycling. Stated differently, they provide "virtual" concurrent engineering for engine structures total-life-cycle-cost.

Introduction

The performance and reliability of propulsion structural systems depend on the interaction of their subsystems which, in-turn, depend on the interaction of their respective components (ref. 1). The performance of a specific component depends on the coupled effects of the system multi-disciplinary interaction on the component response (Fig. 1). Further, the integrated system response depends on the progressive and interacting influence of the coupled service loads/environment at all levels from sub-component, to component, to sub-system, to system. Interaction phenomena of interest include flutter, rotor instability, fatigue, flow separation, nonuniform combustion, blade containment , and noise suppression. The determination of aerothermodynamic system performance has traditionally relied on prototype tests whereas structural reliability has been determined from field data. Over the years, several integrated structural computer codes have been developed. Collectively, the codes constitute an inclusive infrastructure to computa- tionally simulate engine structural performance. The most versatile of these are summarized in Fig. 2. A brief description of the capability of each computer code with a typical result from each follows:

BLASIM (Blade Assessment for Ice Impact) assesses the damage caused by foreign objects impact on engine blades. Examples of foreign objects include bird and ice. Also, this codes is capable of performing a variety of structural analyses including fatigue and flutter (Ref. 2). It consists of special finite element, composite mechanics, approximate design methods, dedicated substructuring and an optimization algorithm (Fig. 3). A typical result obtained from BLASIM is shown in Fig. 4. The strain depends on span location and rotor speed (RPM's) as would be expected from the physics of the situation.

CODSTRAN (Composite Durability Structural Analysis) assesses the progressive structural damage in composite structures from damage initiation to structural fracture (Ref. 3). It is a combination of composite mechanics, finite element structural analysis and damage tracking (Fig. 5). CODSTRAN accounts for all failure modes in composites, residual stresses and environmental effects. The failure modes evaluated using strength criteria thereby by-passing fracture toughness parameters. Though configured primarily for composites, it has been used for conventional metals and even reinforced concrete. It has also been used to simulate blade containment. A typical result is shown in Fig. 6. Two points to note are: (1) The containment process is nonlinear and, (2) thicknesses exist for full penetration or full containment.

CSTEM (Coupled Structural Thermal Acoustic Electromagnetic Tailoring) simulates analysis/design of multi-disciplinary, nonlinear behavior of composite structures (Ref. 4). It combines several 3-D finite element modules for the different disciplines with composites mechanics for polymer matrix, metal matrix and ceramic matrix composites and with an optimization routine (Figs. 7 and 8). It has been used for structural problems, heat transfer, ice formation and more recently for fabrication processing. A typical result is shown in Fig. 9. Tailoring reduced the fan noise by a factor of about six which is substantial. Temperature and moisture increase the fan noise compared to room temperature.

NESSUS (Nonlinear Evaluation of Stochastic Structures Under Stress) is the only code of its kind to quantify expected uncertainties in specified structural response by uncertainties specified at the lowest level of the formulation (Ref. 5). The lowest level usually consists of material properties, structural configuration, support conditions, loading conditions, etc. NESSUS combined finite element structural analysis with probabilistic concepts and can assess reliability and risk (Fig. 10). A typical result is shown in Fig. 11. Note that the probability of failure increases very rapidly from three-parts-in-a thousand failures at 100 hours, to one part-in-two failures at 10,000 hours of exposure.

IPACS (Integrated Probabilistic Assessment of Composite Structures) assesses the uncertainties in composite structures (Ref. 6). It combines NESSUS with probabilistic composites mechanics. Specified uncertainties at the lowest level include (in addition to those in NESSUS): constituent material properties, fabrication parameters laminate configuration variables and environmental effects (Fig 12). IPACS includes a resident data bank for several fibers and matrices. IPACS has been used to evaluate reliability and risk in a variety of composite structures. Typical results are shown in Fig. 13. Only eight of the probable 50 factors (though the factors are not listed here) contribute to the fatigue of the composite wing. This is valuable and hard-to-come-by information for setting material acceptance criteria and processing control tolerances.

T/BEST (Technology Benefits Estimator) assesses the benefits gained by new technology insertions. This computer code may be considered as a "virtual" engine structure development facility. It has been under continuous development at Lewis Research Center for about three years. The computer code is identified as T/BEST (Ref. 7). T/BEST performs computational simulation to estimate the benefits of introducing new technologies into existing or new propulsion systems at any level as shown in Fig. 14. The discipline modules used in T/BEST are: engine cycle (thermodynamic), engine weight, internal fluid mechanics, cost, mission, and coupled structural/thermal/tailoring. The executive system of T/BEST operates on stand-alone or networked workstations. Input files for all modules are generated automatically. T/BEST's modular approach allows for modifications and addition of analyses modules. All modules in T/BEST intercommuni-cate via a central neutral file. The modular structure of T/BEST is shown in Fig. 15. The execution sequence starts with the NNEPWATE (engine cycle) module in a clockwise direction and terminates with graphical display. A typical result is shown in Fig. 16. Obviously the system benefits are substantial across the board. This explains, in part, the increased effort on application of composites to aircraft engines.

HS/HTCS (Hierarchical Simulation of Hot Composite Structures) assesses the structural behavior of hot composite structures made from metal and ceramic matrix composites. Several different computer codes are included in this hierarchical structure as shown in Fig. 17. Each of these codes simulates a specific behavior at a specific scale starting from nanomechanics , through structural tailoring. The codes that have been used most frequently include METCAN (Metal Matrix Composite Analyzer, Ref. 8), CEMCAN (Ceramic Matrix Composite Analyzer, Ref. 9), and MMLT (Metal Matrix Laminate Tailoring, Ref. 10). A typical result from MMLT is shown in Fig. 18. It is very interesting indeed that processing conditions are cycle requirements specific. In this case, process tailoring is not cost effective.

Conclusions

Select codes are available at the Structures and Acoustics Division at NASA Lewis Research Center to computationally simulate all aspects of engine structural response including tailoring, reliability and risk and benefits of new technology insertion. Typical results obtained from these codes are: (1) blade ice impact, (2) fan blade composite containment, (3) composite acoustic fatigue, (4) reliability of turbine blade, (5) reliability of fatigue life of a composite airfoil section, (6) benefits gained by using composites in engines and, (7) metal matrix laminate tailoring for improved load carrying capacity. Typical results obtained from these computational methods illustrate that just about any engine structures configuration from any material and from any fabrication process, can be effectively simulated. Stated more concisely, collectively these codes constitute a "virtual" concurrent engineering and "virtual" engine structures development facility.

References

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3. Chamis, C.C., Murthy, P.L.N and Minnetyan, L: Progressive Fracture of Polymer Matrix Composite Structures: A New Approach. NASA TM 105574, January 1992.

4. Hartle, M., et. al, "CSTEM User's Manual," NASA Document , 1990.

5. "Probabilistic Structural Analysis for Select Space Propulsion System Structural Components," Annual Report by SwRI, Rocketdyne, University of Arizona, MARC Analysis Corp. and Columbia University for NASA LeRC, Contract NAS3-24389, 1986.

6. Chamis, C. C. and Murthy, P. L. N.: Probabilistic Composite Analysis. NASA CP 3104, Part 2, 1991, pp. 891-900.

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10. Morel, M.R., Saravanos, D.A. and Chamis, C.C., "Tailored Metal Matrix Composites for High Temperature Performance", NASA TM 105816, 1992.

Questions

Q. Do you expect by just using this smart casing you get the 10 Db reduction, that's what you are concluding?

A. The smart casing was primarily for clearance control but one could design an acoustic pressure smart structure concept as well.

Q. Those were two separate cases? You used other techniques for obtaining this result? I would expect dual auto system integration technology with noise technology to bring the 10Db down.

A. The treatment was considered by itself and the clearance was considered by itself.

Q. In the Navy we have done similar things on this smart casing. Changing the contour of the cell. We only get very small benefits (A . Small benefits is what we find here too). So you still got to rely on your technology, on your noise sources.

A. So then in that case you have to tune the cavity and maintain tip clearance. One is to select a design in such a way that at the operating conditions we keep clearance and maintain desirable cavity features. Which means you also have to have a very stiff casing. A smart case constructed with controlled circumferential and radial stiffness so that clearance requirements and cavity features are simultaneously satisfied.

Q. The tip clearance alone will not reduce noise level. You have to do a cavity optimization as well ?

A. Yes, you have to couple the two. These were not coupled in the investigation we performed.

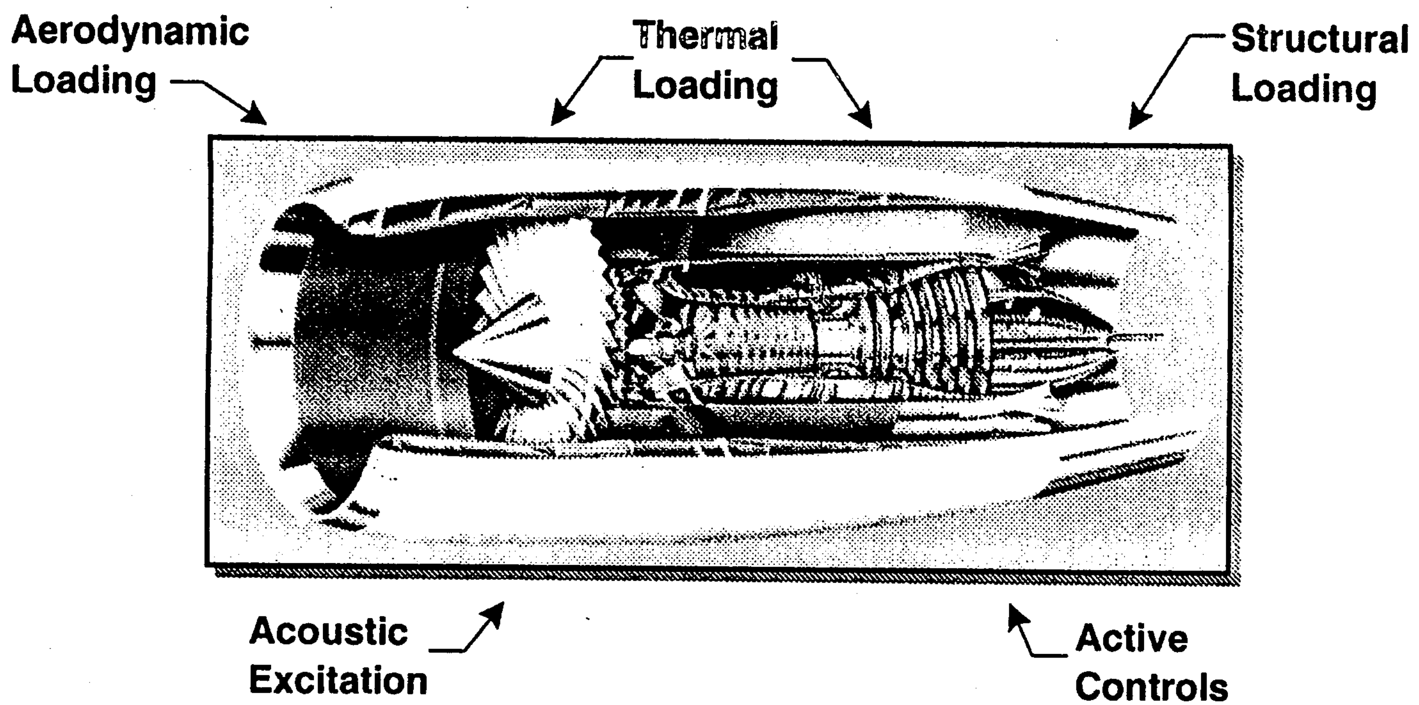
Q. With respect to the ceramics, what was the input on airplane cost?

A. Those were based on Boeing 777 estimated costs.

Q. Yes, but in that particular example what was the cost impact on the airplane?

A. The cost on the airplane? As a matter of fact it did not turn out to be very high indeed. It turned out to be about the same. This was based on the material that was ready to use. We did not include cost of development of material to be used. That should have been clarified. Once the material is developed , the cost is even less because you reduce maintenance cost. And besides in addition, there are savings in fuel and in the reduced cooling plumbing which more than compensates for the higher material costs.

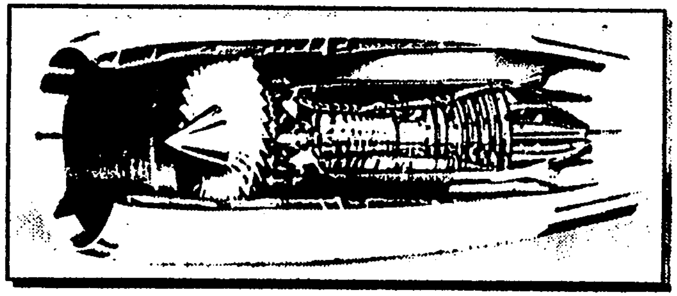
Engine Components Under Service-Environment Loadings



The structure is the natural multi-discipline integrator.

Fig. 1

Engine Structures Computational Simulation Methods



BLASIM -- *Low Impact Evaluation*

CODSTRAN -- *Progressive Structural Fracture Assessment*

CSTEM -- *Acoustic Fatigue and Coupled Multi-Discipline Analyses.*

NESSUS -- *Reliability/Risk of Metallic Structures*

IPACS -- *Reliability/Risk of Composite Structures*

T-BEST -- *System-type Benefits Accrued from Structural Concepts/Technologies*

HS/HTCS -- *Inclusive of All Aspects of High Temperature Metal Matrix Composite Structures.*

Fig. 2

BLASIM CODE CAPABILITIES

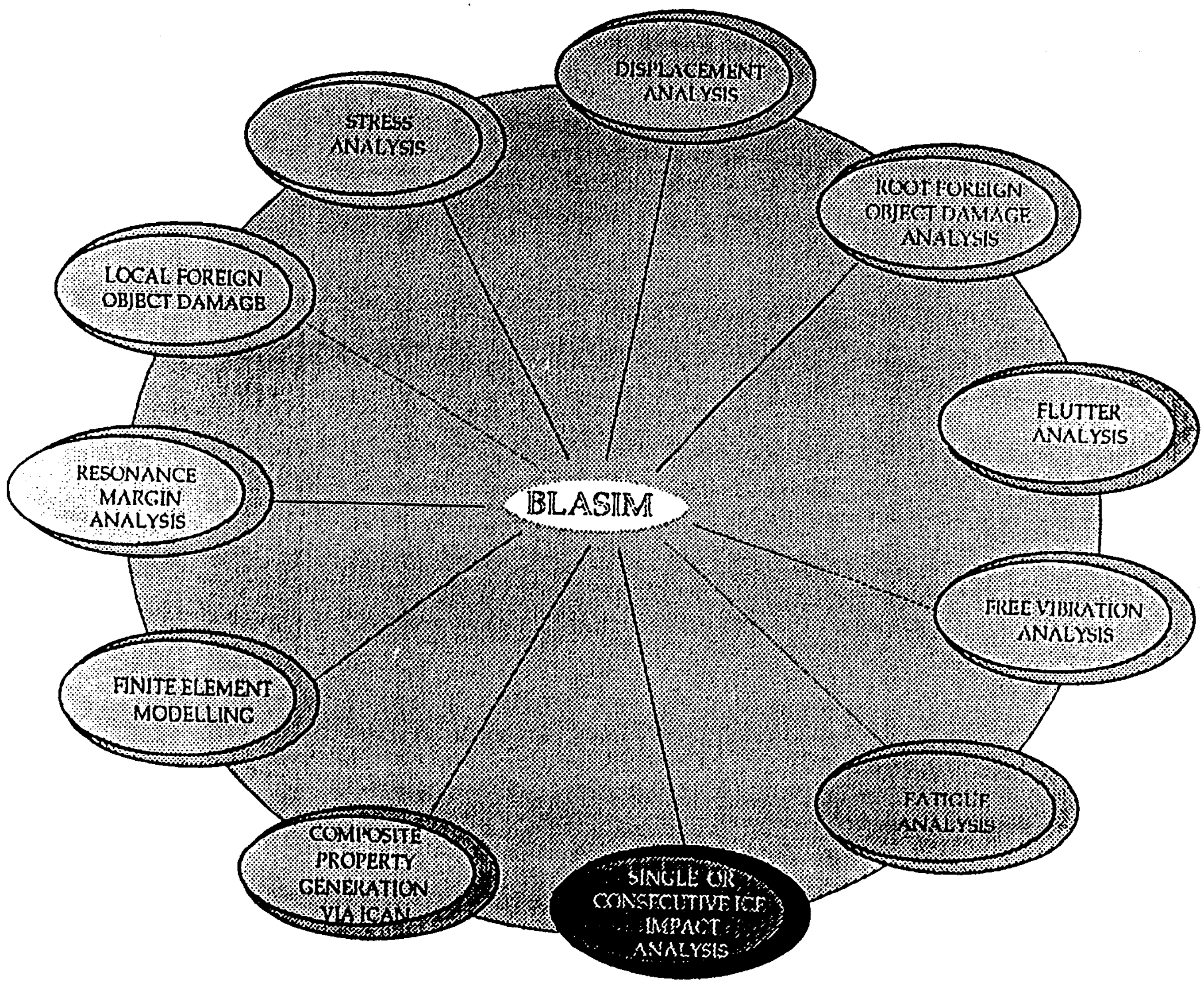


Fig. 3

EFFECT OF IMPACT LOCATION ON ROOT RESPONSE

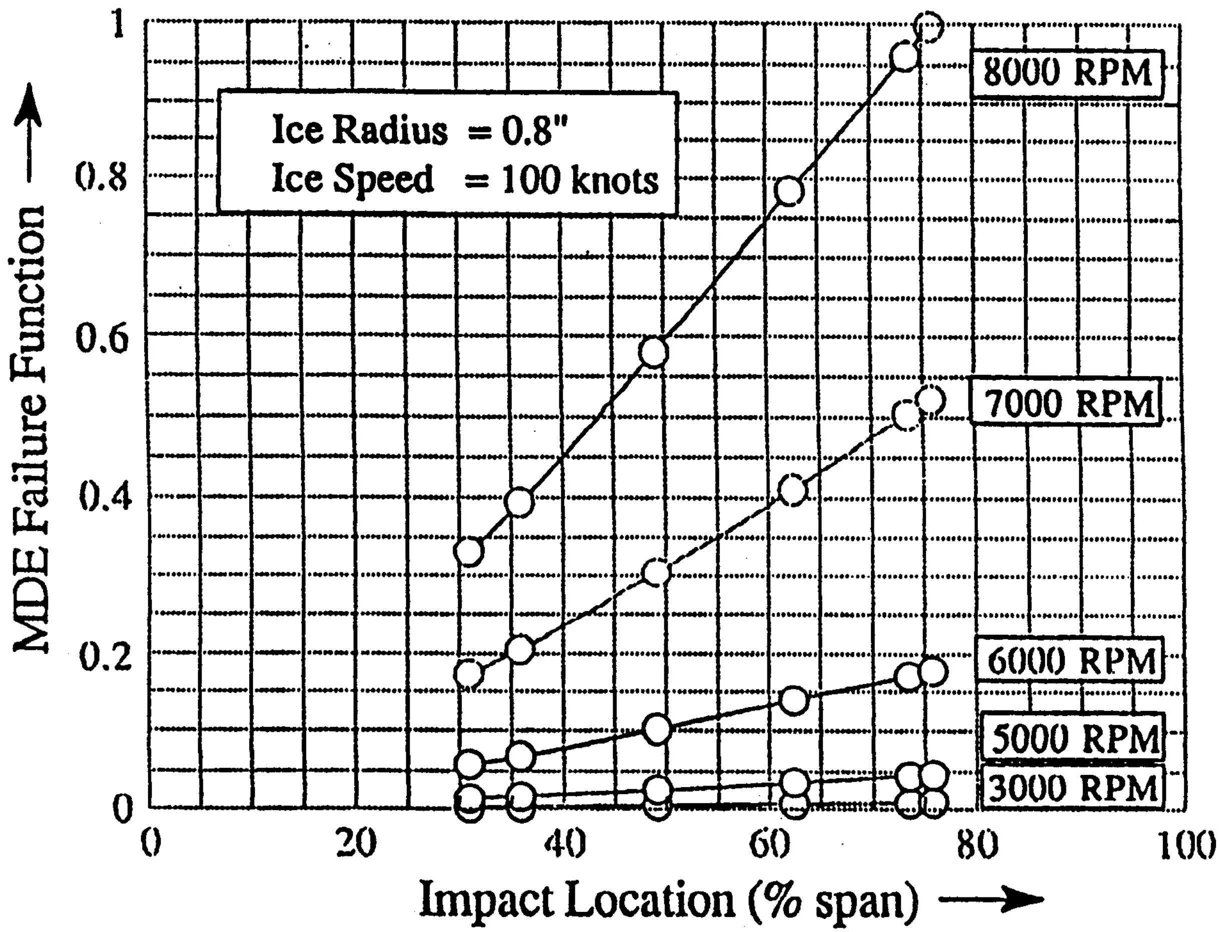


Fig. 4

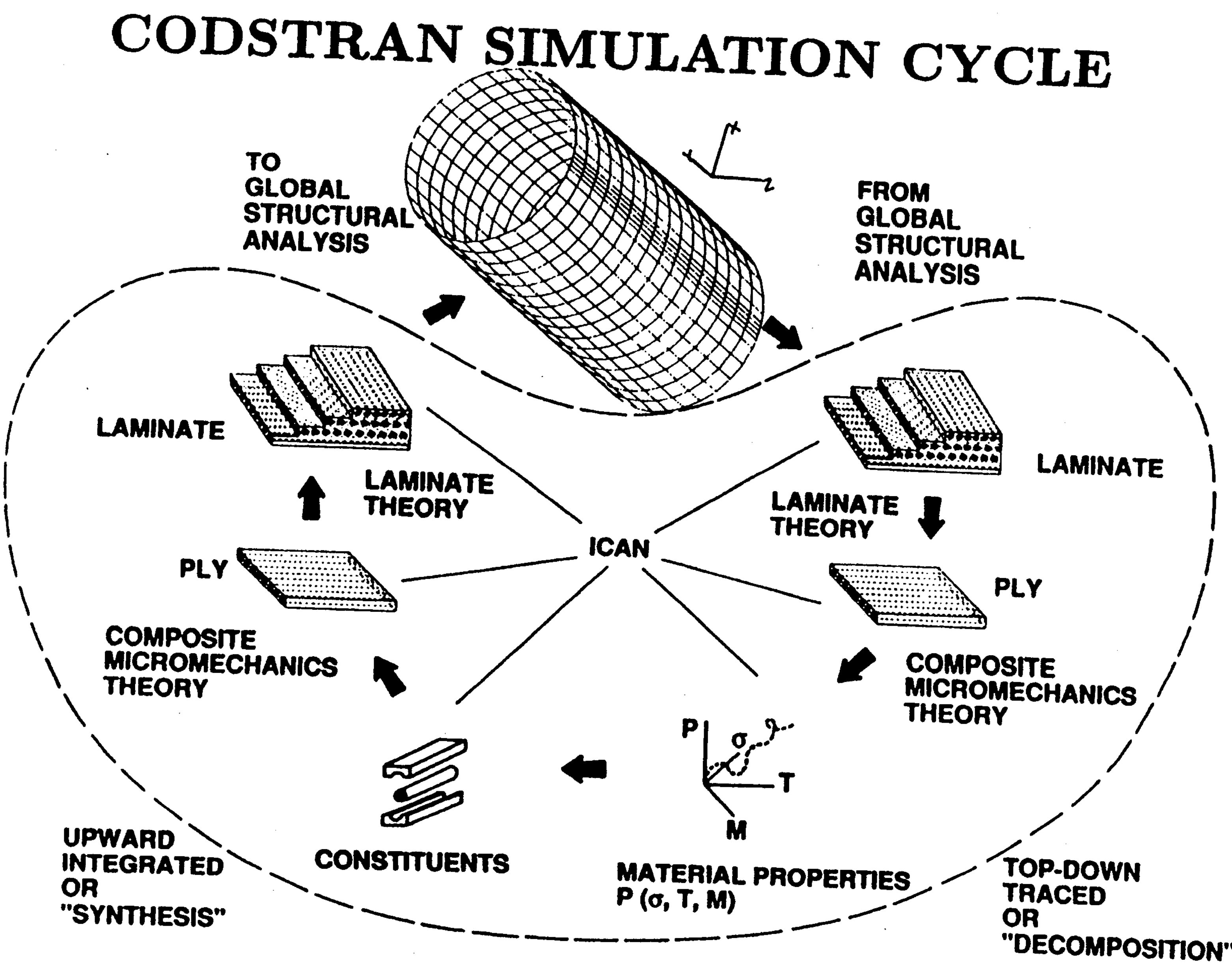

CODSTRAN SIMULATION CYCLE
TO GLOBAL STRUCTURAL ANALYSIS
FROM GLOBAL STRUCTURAL ANALYSIS
LAMINATE
LAMINATE THEORY
PLY
COMPOSITE MICROMECHANICS THEORY
ICAN
LAMINATE
LAMINATE THEORY
PLY
COMPOSITE MICROMECHANICS THEORY
P
σ
T
M
CONSTITUENTS
MATERIAL PROPERTIES P (σ, T, M)
UPWARD INTEGRATED OR "SYNTHESIS"
TOP-DOWN TRACED OR "DECOMPOSITION"

Fig. 5

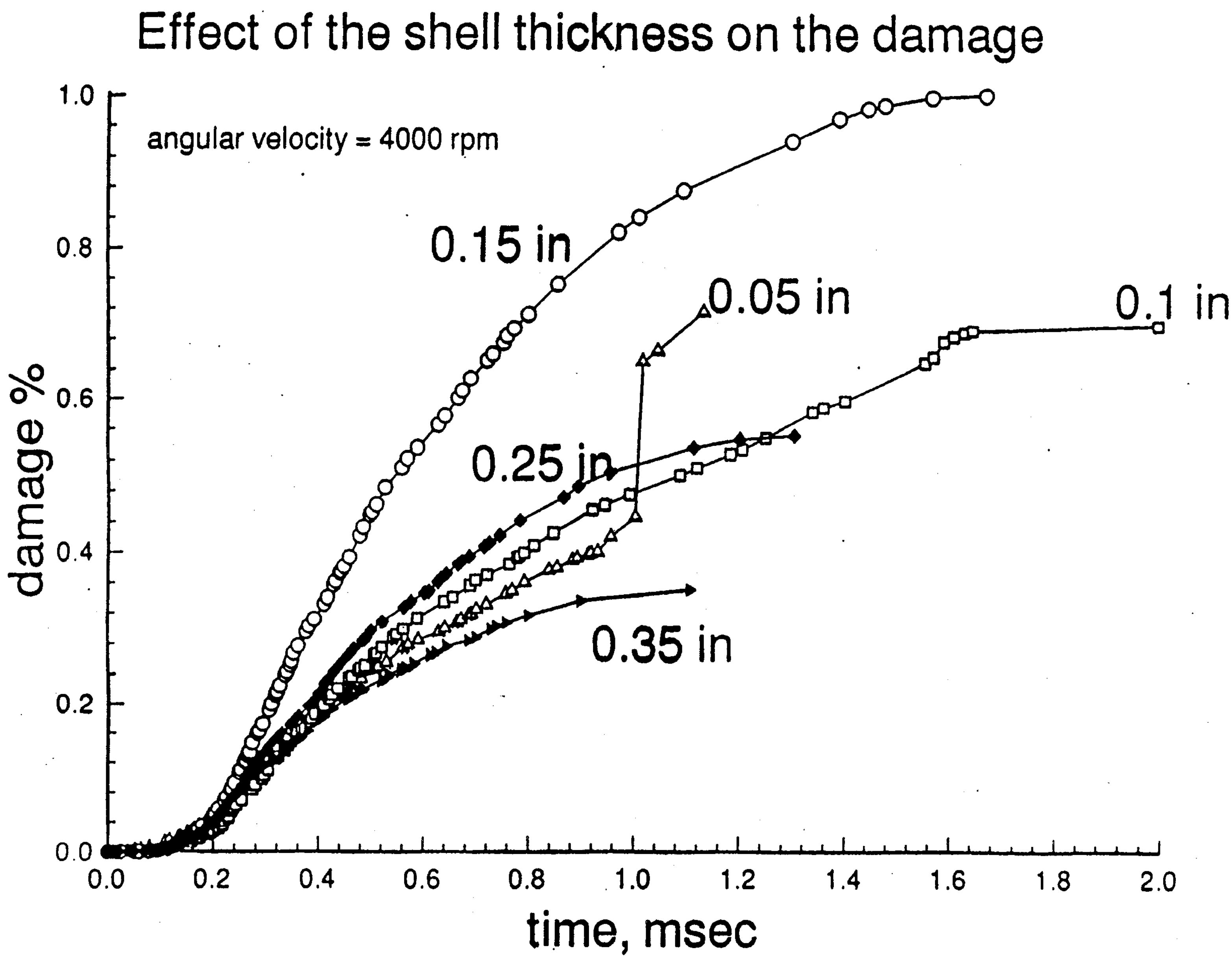

Effect of the shell thickness on the damage
angular velocity = 4000 rpm
0.15 in
0.05 in
0.1 in
0.25 in
0.35 in
damage %
time, msec
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Fig. 6

Multidisciplinary Tailoring - Modular Structure

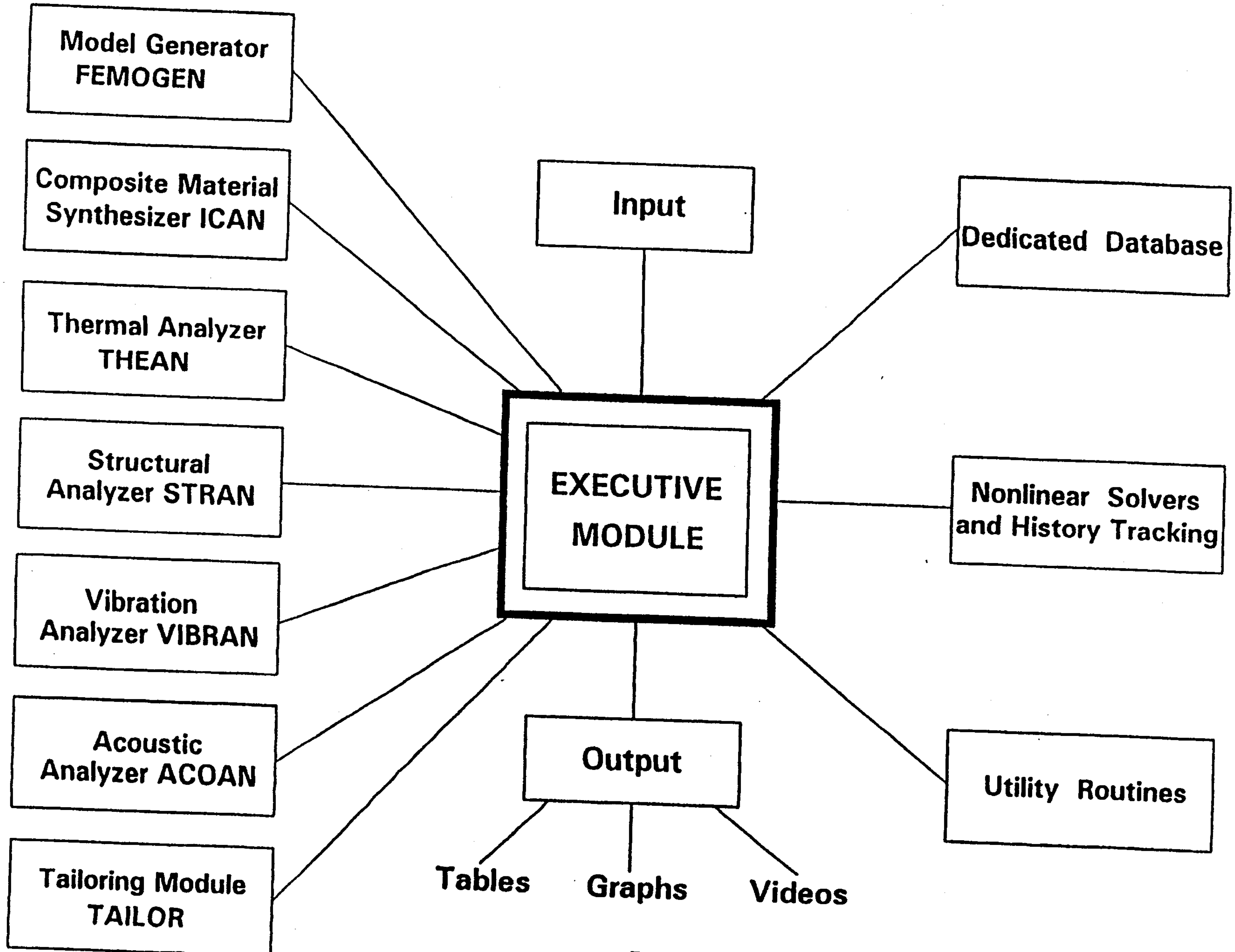
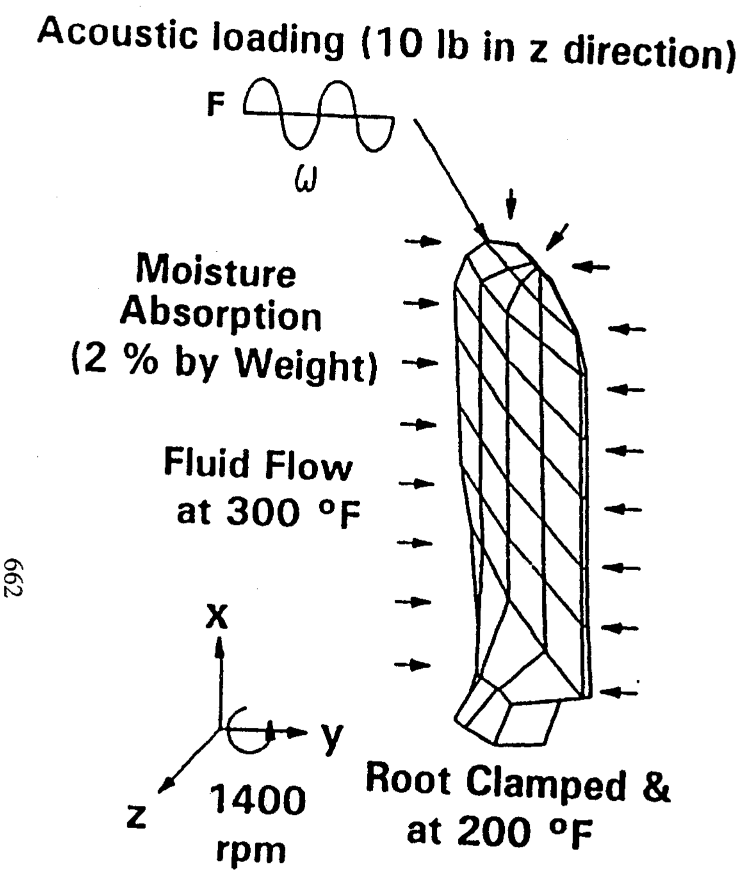
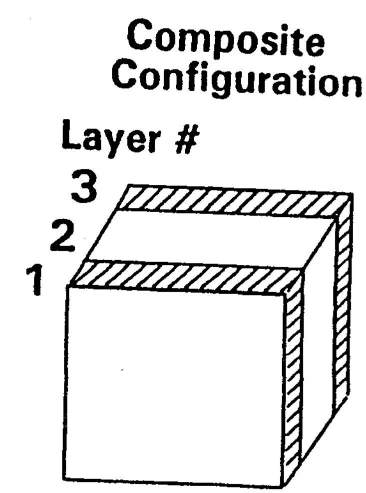


Fig. 7

Multi-material Multi-layered Composite Fan Blade
Initial Design under Multidisciplinary Loadings





Initial Design Values

Layer #	Material	Thickness (fraction)	Orientation w.r.t. x-axis (deg.)
1	T300/IMHS	0.25	30
2	Titanium	0.5	0
3	T300/IMHS	0.25	30

Fig. 8

Acoustic Tailoring of Composite Fan Blades - Effect of Environments

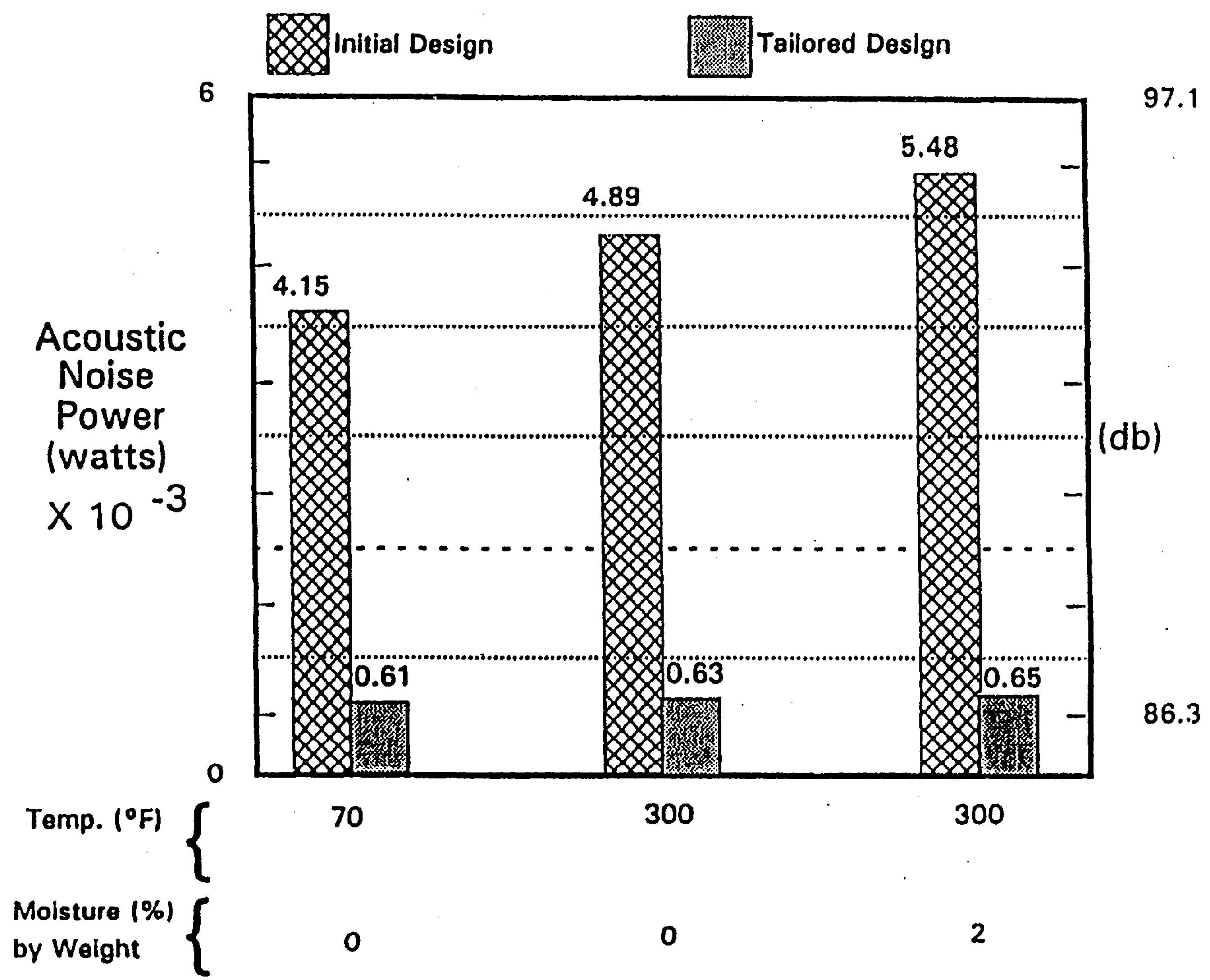


Fig. 9

PROBABILISTIC SIMULATION OF COMPONENT RELIABILITY USING CLS COUPLED WITH PSAM AND PMBM

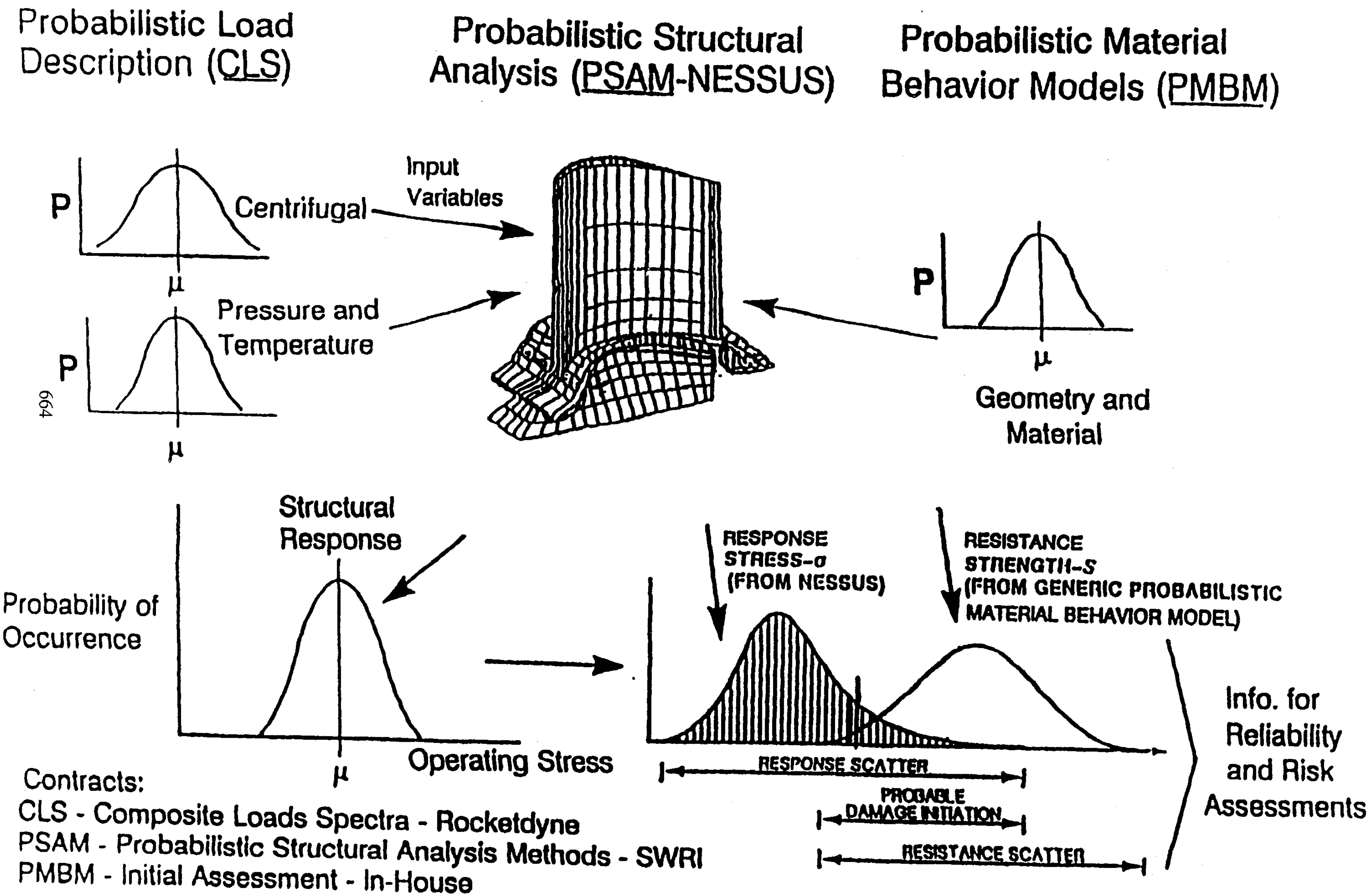


Fig. 10

Results for the Creep Rupture Analysis

- By Varying *t*, a Distribution of Failure Probabilities can be Generated
- FEM Calculations are not Required for Each New t — only P2 and the Resulting Probability of Failure are Computed
- More Accurate (but Significantly More Costly) Combined Analysis Shows the Proposed Approach to be Efficient and Acceptably Accurate

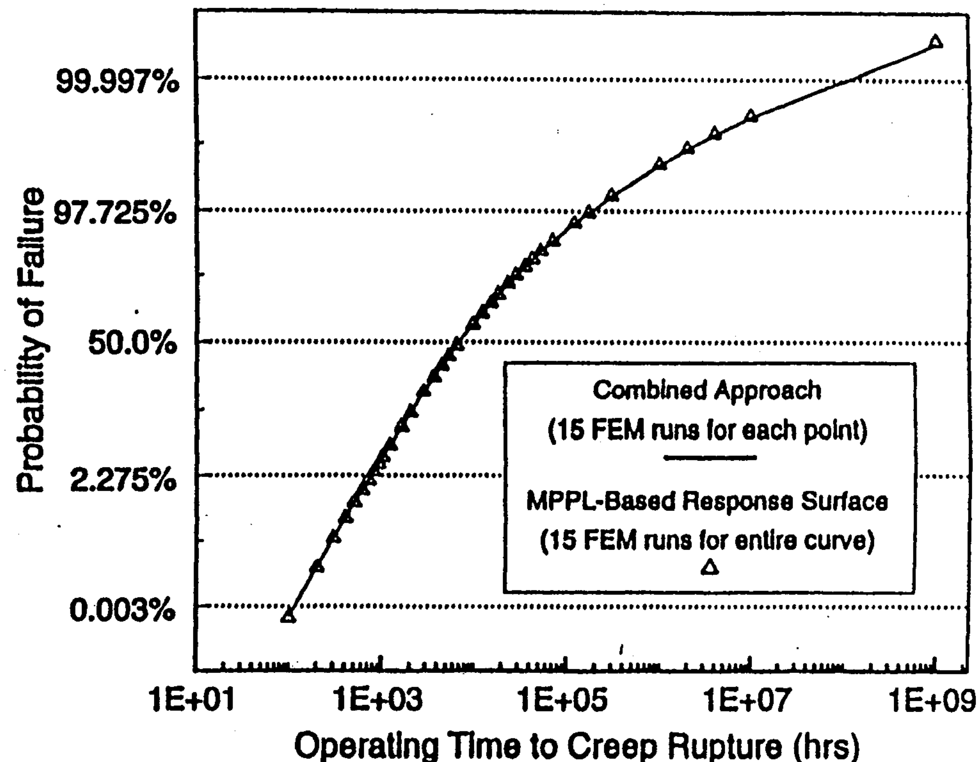
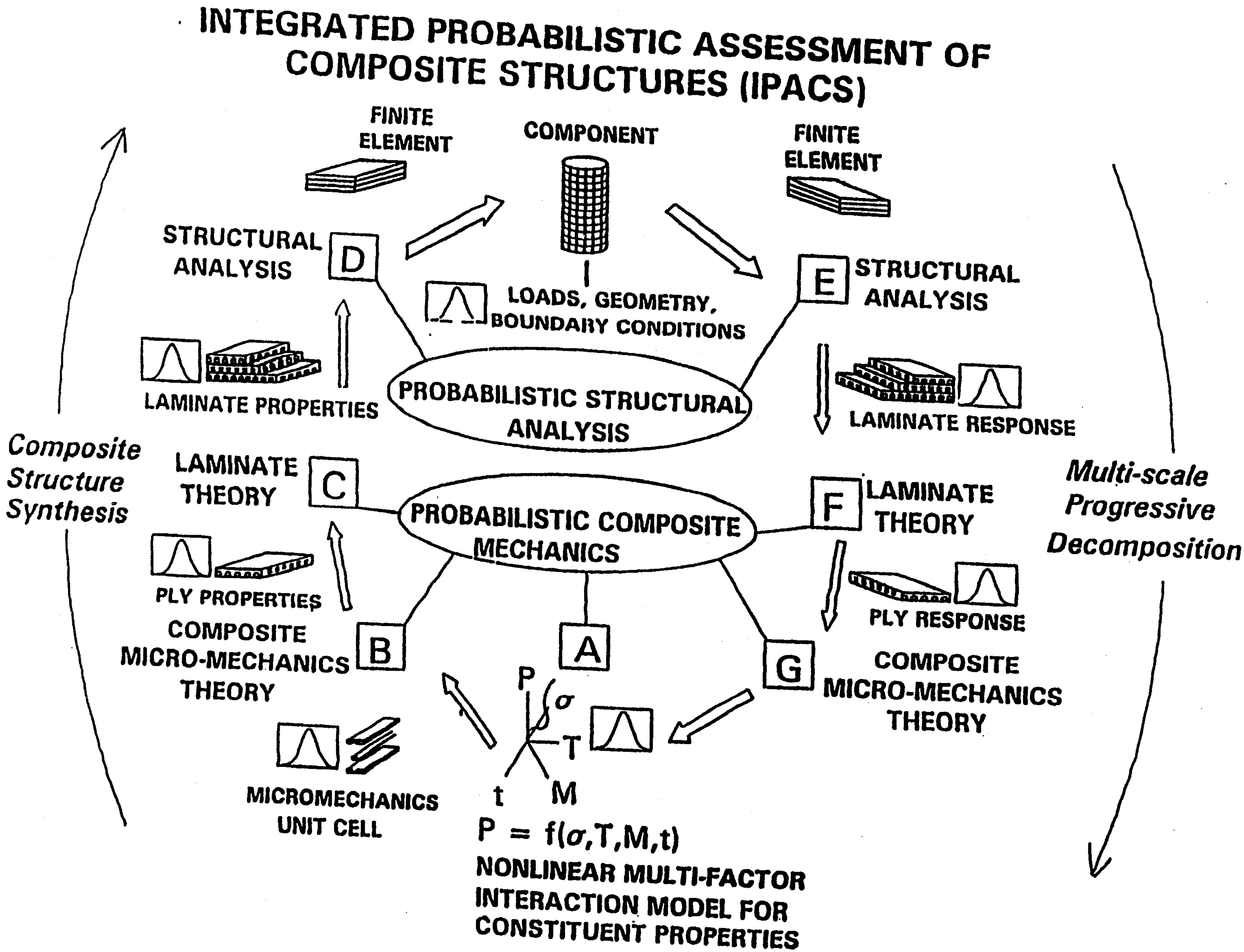


Fig. 11



INTEGRATED PROBABILISTIC ASSESSMENT OF COMPOSITE STRUCTURES (IPACS)
FINITE ELEMENT
COMPONENT
FINITE ELEMENT
STRUCTURAL ANALYSIS
D
LOADS, GEOMETRY, BOUNDARY CONDITIONS
E
STRUCTURAL ANALYSIS
LAMINATE PROPERTIES
PROBABILISTIC STRUCTURAL ANALYSIS
LAMINATE RESPONSE
Composite Structure Synthesis
LAMINATE THEORY
C
PROBABILISTIC COMPOSITE MECHANICS
F
LAMINATE THEORY
Multi-scale Progressive Decomposition
PLY PROPERTIES
PLY RESPONSE
COMPOSITE MICRO-MECHANICS THEORY
B
A
G
COMPOSITE MICRO-MECHANICS THEORY
P
σ
T
t
M
MICROMECHANICS UNIT CELL
P = f(σ,T,M,t)
NONLINEAR MULTI-FACTOR INTERACTION MODEL FOR CONSTITUENT PROPERTIES

Fig. 12

Compressive Fatigue Life of a Composite Wing

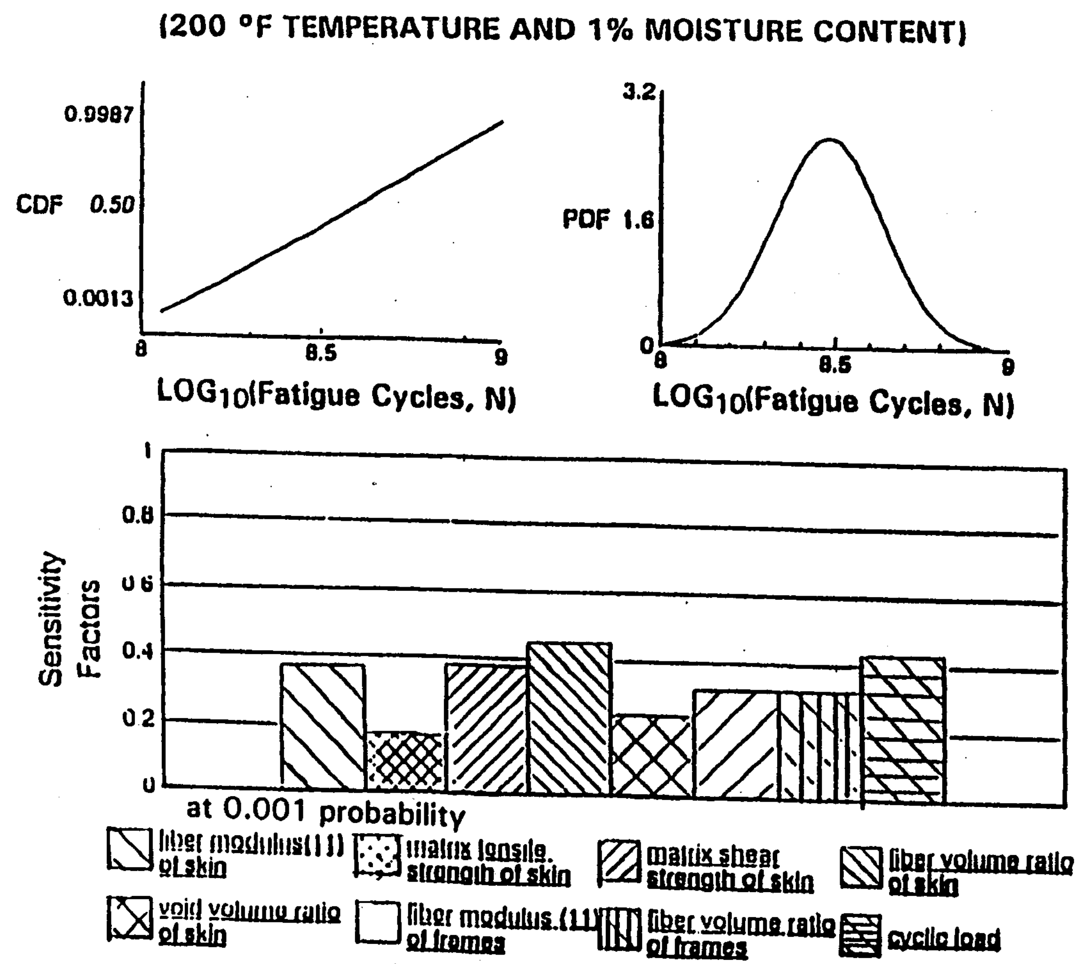


Fig. 13

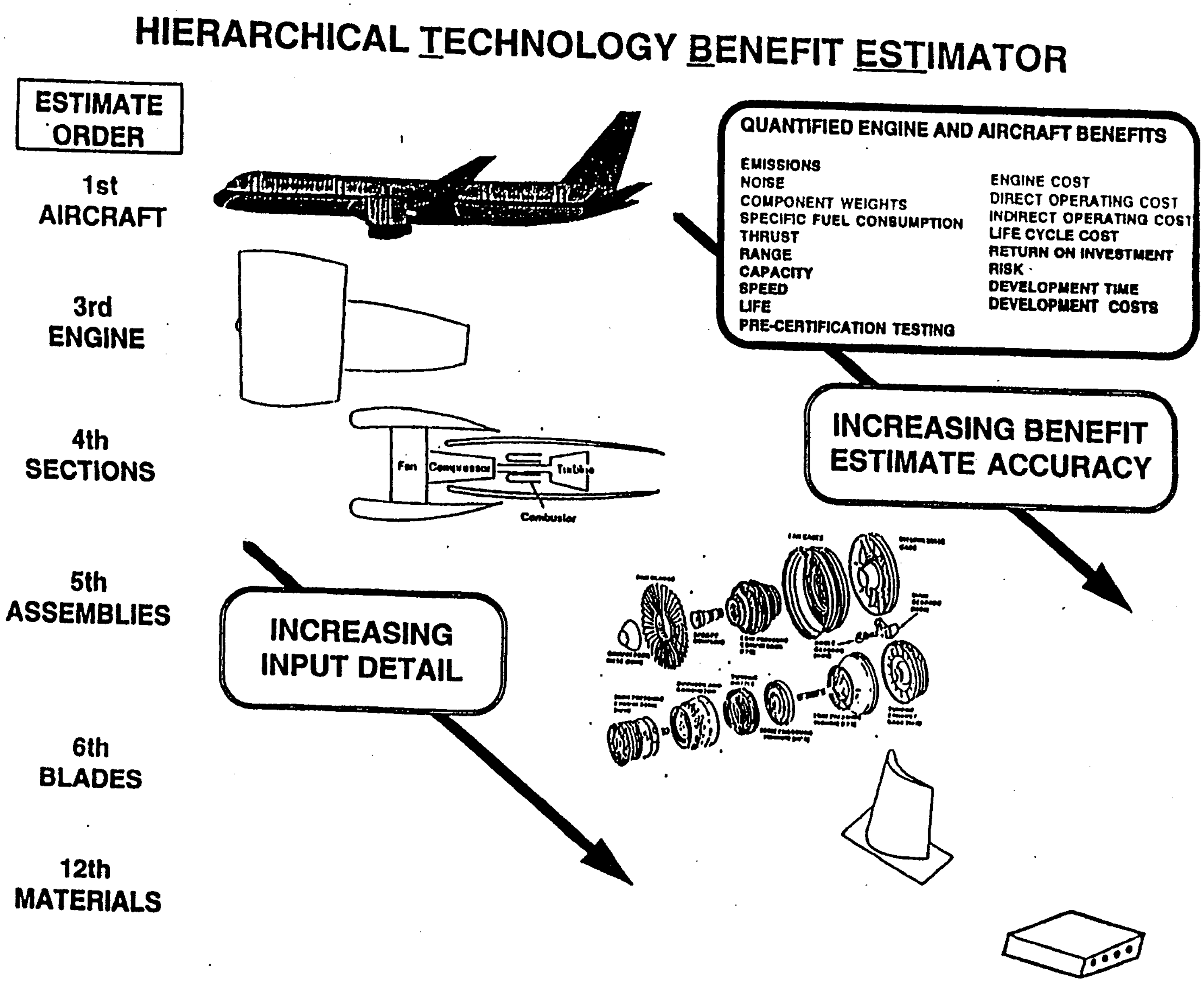

HIERARCHICAL TECHNOLOGY BENEFIT ESTIMATOR
ESTIMATE ORDER
1st AIRCRAFT
3rd ENGINE
4th SECTIONS
5th ASSEMBLIES
6th BLADES
12th MATERIALS
Fan
Compressor
Turbine
Combustor
QUANTIFIED ENGINE AND AIRCRAFT BENEFITS
EMISSIONS
NOISE
COMPONENT WEIGHTS
SPECIFIC FUEL CONSUMPTION
THRUST
RANGE
CAPACITY
SPEED
LIFE
PRE-CERTIFICATION TESTING
ENGINE COST
DIRECT OPERATING COST
INDIRECT OPERATING COST
LIFE CYCLE COST
RETURN ON INVESTMENT
RISK
DEVELOPMENT TIME
DEVELOPMENT COSTS
INCREASING BENEFIT ESTIMATE ACCURACY
INCREASING INPUT DETAIL

Fig. 14

T/BEST Modular Structure

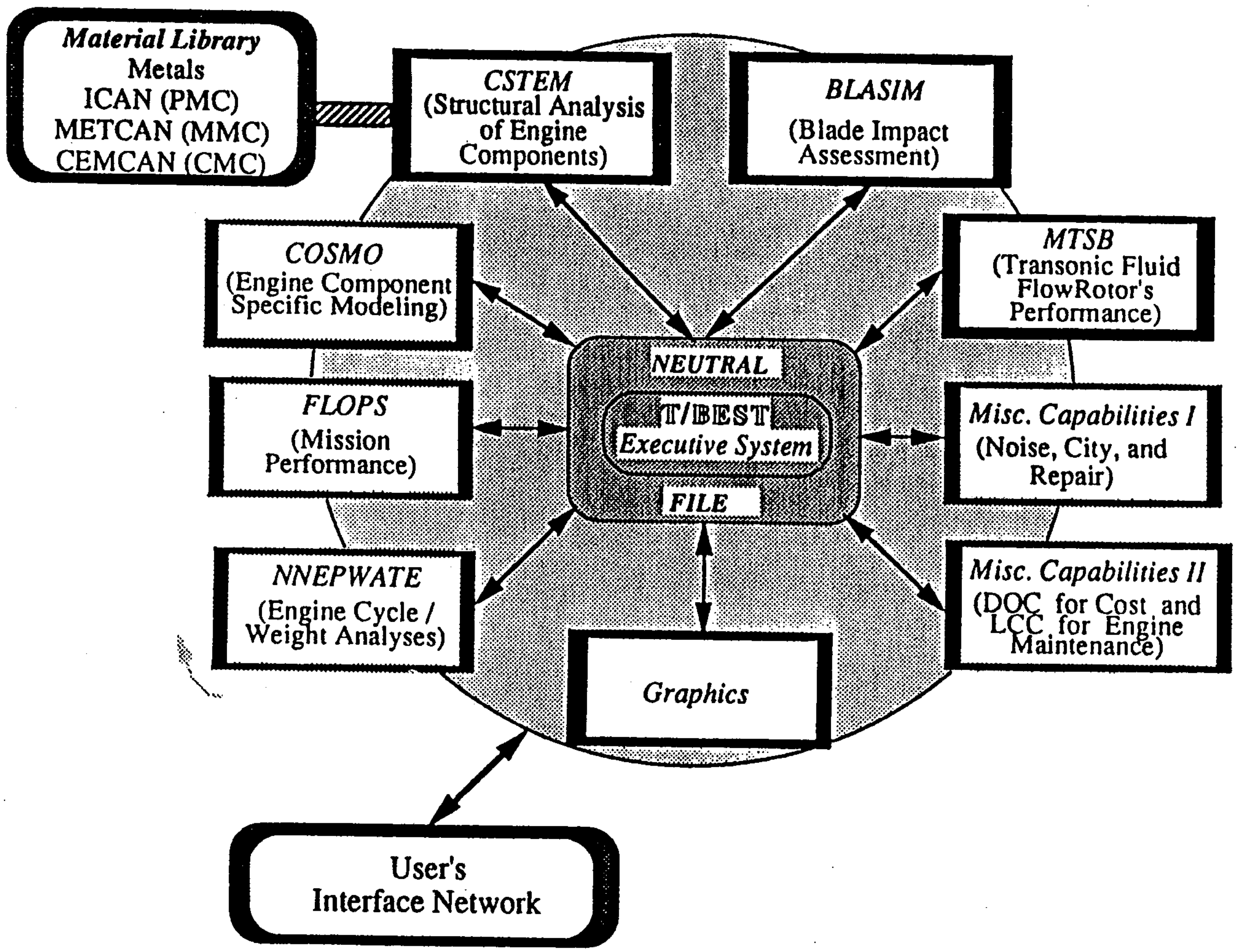


Fig. 15

Aircraft Operating Cost Benefits of Advanced Composites Over Conventional Metals - Subsonic Transport

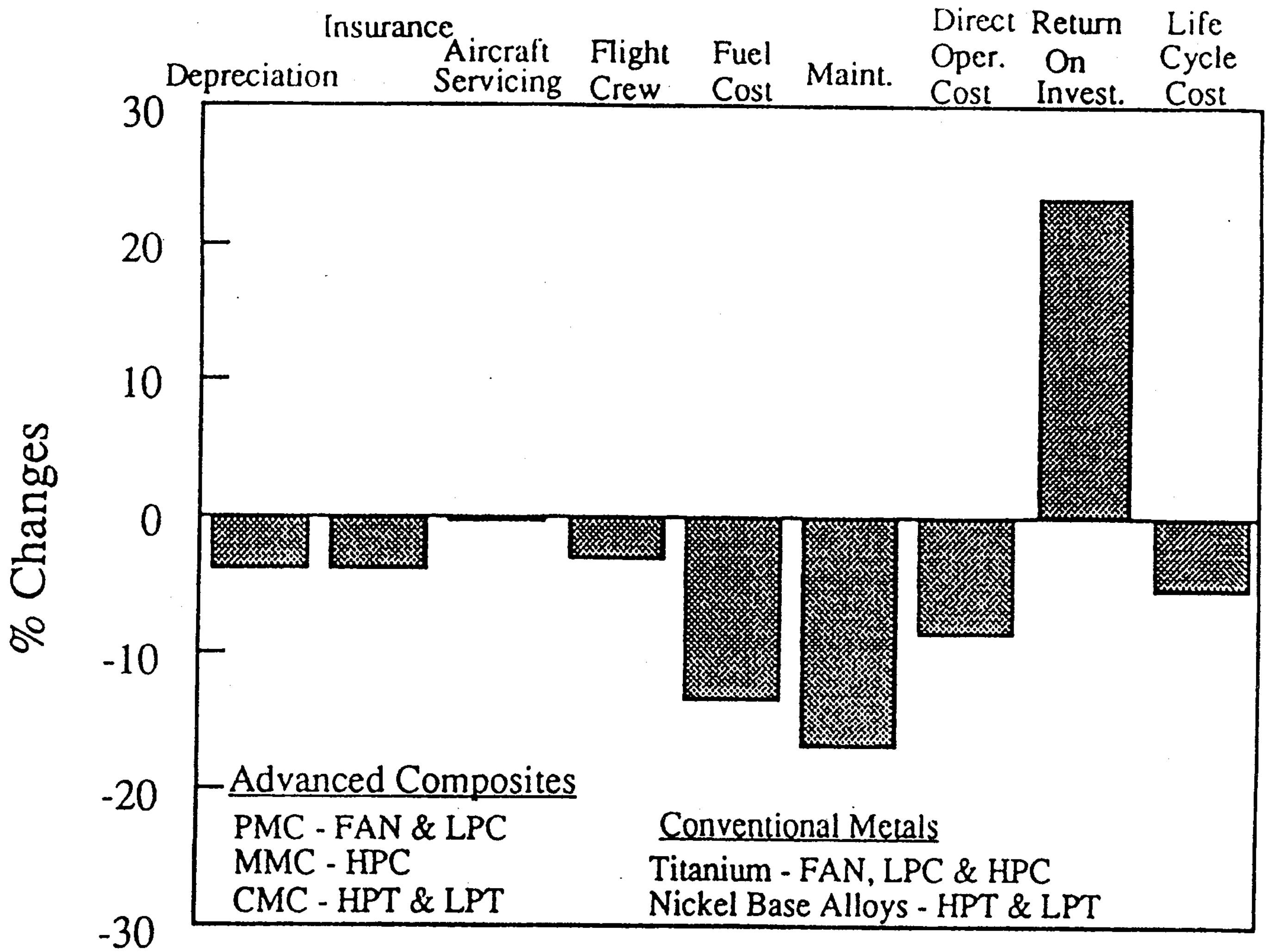


Fig. 16

Hierarchical Computational Simulation/Tailoring of Hot Composite Laminates/Structures

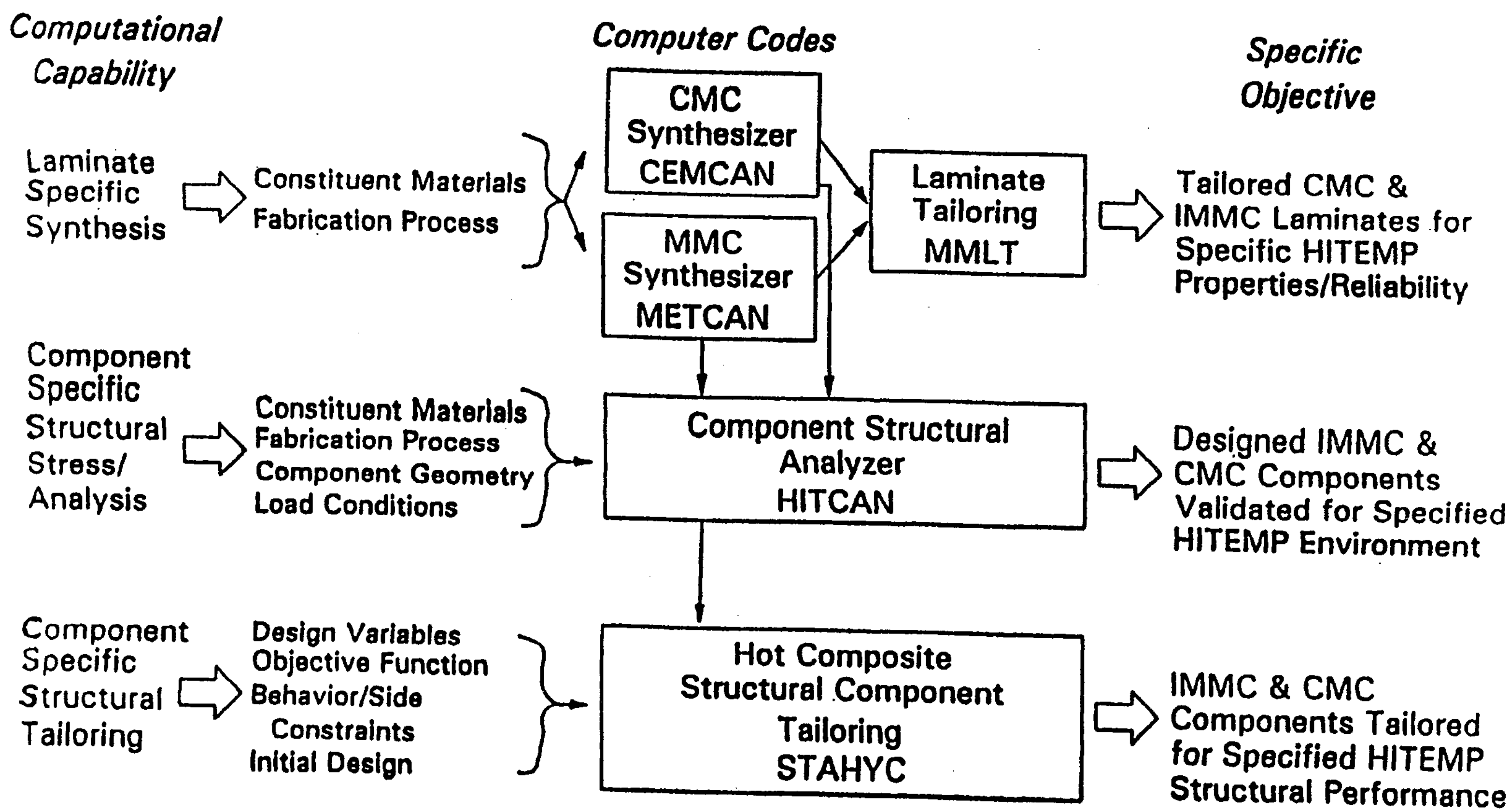


Fig 17

Effect of Optimal Processing on Fatigue Life

[0] SCS6/Ti-24Al-11Nb, 0.35 FVR (70 °F (23 °C), R = 0.1)

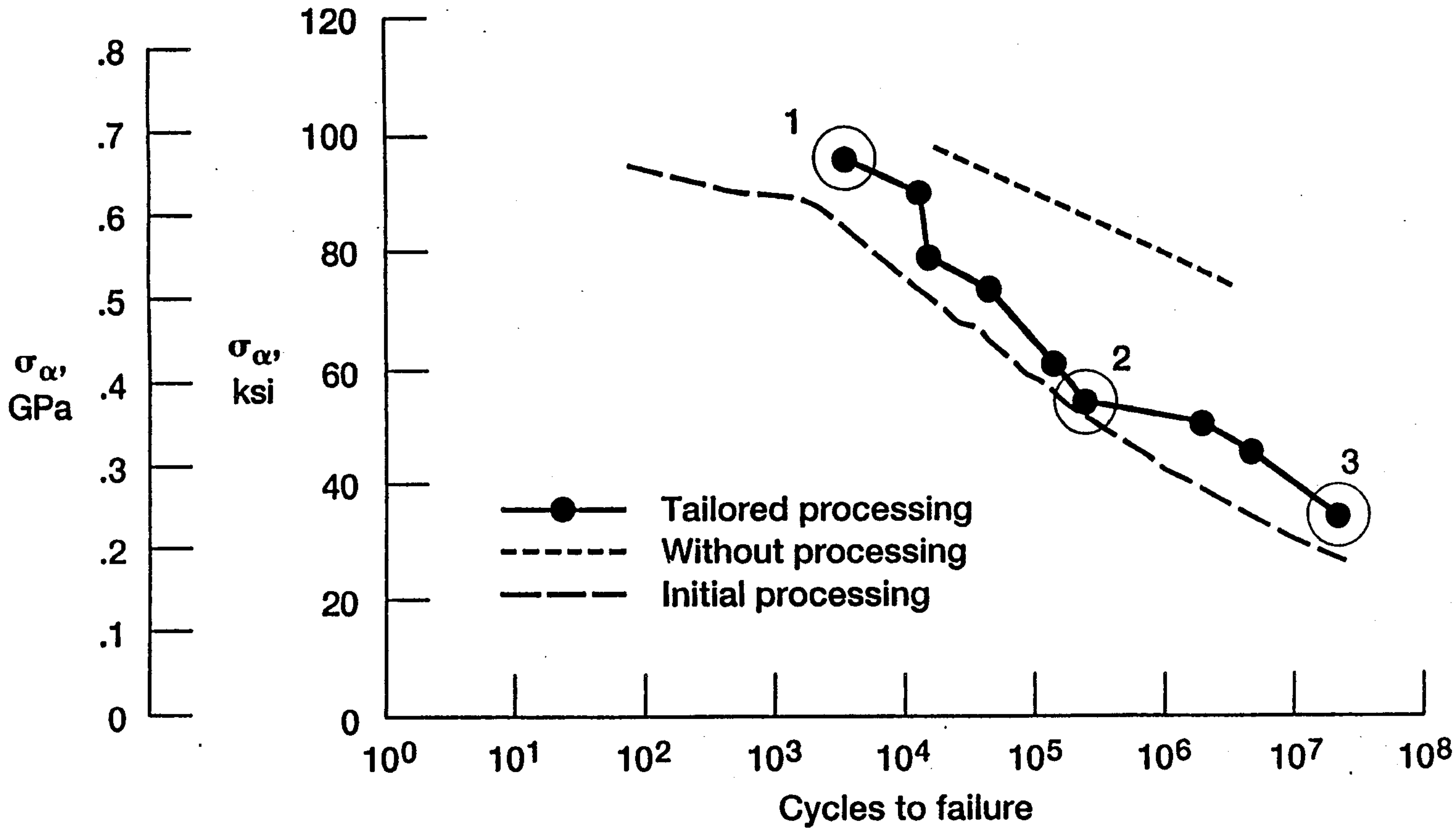


Fig. 18